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Extended Abstracts

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Tailoring Stress Waves in 2-D Highly Nonlinear Granular Crystals: Simulations and Experiments

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Abstract: We study the propagation of elastic stress waves in two-dimensional highly nonlinear granular crystals composed of square packings of spheres with and without cylindrical intruders, via experiments and numerical simulations. By varying the intruder material, we show the ability to alter the propagating wave front characteristics. Experiments agree well with discrete particle simulations.

Granular crystals are materials composed of ordered arrangements of particles in contact with each other, characterized by a highly nonlinear dynamic response. The transient dynamic response of one-dimensional highly nonlinear (uncompressed) granular crystals has been studied extensively[1,2], however few reports have explored wave propagation in two-dimensional systems[3]. The present work investigates the propagation of stress waves, or acoustic waves, in highly nonlinear two-dimensional granular crystals composed of a squared array of steel spheres and interstitial cylindrical intruders (Figure 1). Specifically, we analyze the influence of underlying particle composition on the wave front shape. We report that it is possible to substantially alter the shape of the wave front traveling through the system after impulsive loading by methodically varying the intruder material. These findings could lead to the development of new shock protecting materials and acoustic filters.

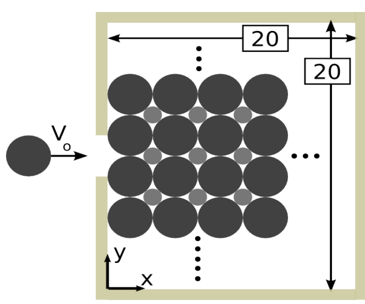

Figure 1 Schematic diagram of the experimental setup.

Numerical simulations were performed using a discrete particle model, in which each sphere or cylinder is modeled as a point mass connected by nonlinear springs. Hertzian potential[4] is used to model the sphere-sphere and sphere-wall interactions and a similar potential[5] is used to model the sphere-cylinder force displacement relation. Dissipative terms, such as friction, were not included in the simulations. Material properties chosen for the simulations are given in Table 1.

Experiments were performed on self-standing crystals assembled within a confining box made of delrin-lined walls (Figure 1). The array of particles included a 20 by 20 array of large steel spheres (19.05 mm diameter) with small interstitial intruders (7.89 mm diameter and 19.05 mm height). A striker-sphere identical to the particles composing the array was used to generate stress waves between two central particles in the array. The striker velocity was recorded with an optical velocimeter just before impact, and the recorded value was used as input in the numerical simulations. Several custom-fabricated sensor particles, instrumented with calibrated miniature tri-axial accelerometers, were positioned in selected locations in the array. The recorded accelerations were then compared with the acceleration of the center of mass of each particle obtained from the numerical simulations.

Material	Mass density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio
Stainless Steel (type 316)	8000	193	0.30
Aluminium	2740	69	0.33
Teflon (PTFE)	1200	0.5	0.46

Table 1 Material properties used in numerical simulations.

Experiments were performed on the square packing of spheres with and without the presence of the cylindrical intruders, and were shown to be in good agreement with the numerical simulations (see Figure 2, comparing experimental and simulation results for an array without intrud-

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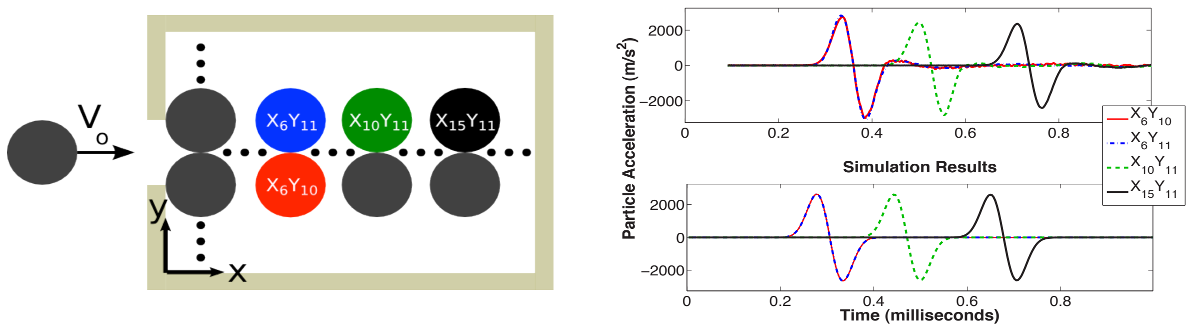

Figure 2 The left figure shows locations of sensor particles in the experimental setup (V_o = 0.29 m/s). The right figure compares experimental results (top right) with the simulation results (bottom right) for each of the sensor locations.

ers). In the absence of cylindrical intruders, the crystal was shown to support the propagation of solitary waves with comparable properties to the solitary waves previously observed in one-dimensional systems[1,2].

Numerical simulations showed the ability to significantly alter the stress wave front by introducing indruder particles of variable materials. A crystal composed of a squared array of particles without intruders supports the formation and propagation of highly nonlinear solitary waves along the two central chains (in line with the impact direction) and along the side of the crystal (following a quasi one-dimensional behavior, see Figure 3a). However, when cylindrical intruders were included the shape of the wavefront was observed to vary. When Teflon cylinders were used as intruders (Figure 3b) the wave front remained highly directional, similar to the case where intruders are absent, but the initial pulse begins to spread and shed energy in trailing pulses. The use of aluminium intruders allowed spreading of the wavefront into a triangular pattern (Figure 3c). Finally, when stainless steel intruders were used, we observed a nearly circular wavefront (Figure 3d) with particle velocities distributed over a larger area of the crystal. The ability to control the stress wave properties in these granular cystals may allow for the development of new wave-tailoring materials which could be used, for example, as protective layers capable of redirecting and trapping impact energy.

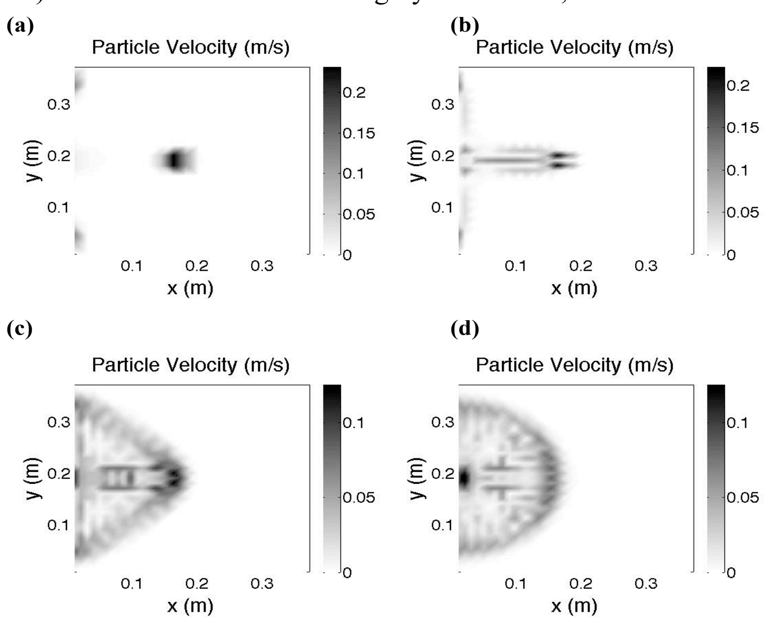

Figure 3 Numerical results showing the wave front shape in terms of particle velocity magnitude at simulation time 0.35 ms after the striker impact (V_o = 0.6 m/s) for test configurations composed of steel spheres in a square packing with **(a)** no intruders **(b)** PTFE intruders **(c)** aluminium intruders and **(d)** steel intruders.

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